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A Simple Method for Range Finding via Laser Triangulation

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INTRODUCTION

For determining range via triangulation, the baseline distance between source and sensor as well as sensor and source angles are used in theory. Figure 1 shows the configuration for triangulation ranging (Everett, 1995):

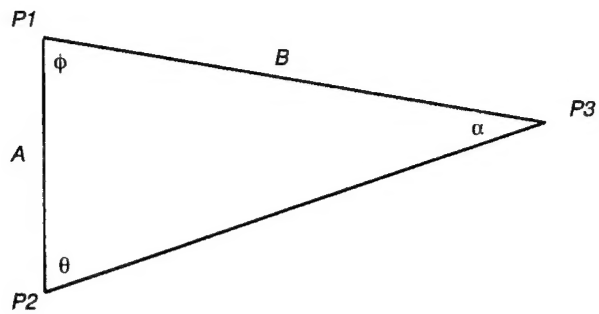

Figure 1. Configuration for triangulation ranging.

P1 and *P2* represent two reference points (e.g., camera and laser source), while *P3* is a target point. The range *B* can be determined from the knowledge of the baseline separation *A* and the angles θ and ϕ using the law of sines:

$$B = A\frac{\sin\theta}{\sin\alpha} = A\frac{\sin\theta}{\sin(\theta + \phi)} \tag{1}$$

In practice this is difficult to achieve because the baseline separation and angles are difficult to measure accurately. We have demonstrated a technique for obtaining range information via laser triangulation without the need to know A, ϕ, and θ. This technique was successfully implemented on a laser range-finding system on the NRaD ModBot (Modular Robot) test bed.

PROCEDURE

Figure 2 diagrams the setup of our laser and camera. The camera is represented by the image plane, focal point, and optical axis. The laser is directly above the camera, although its exact position is unimportant (we will only deal with the beam of light, represented by line *CE* in the diagram).

The laser is positioned so that the path of the laser and the optical axis form a vertical plane. Point P is the target of interest. We wish to find x, the projection of point P on the optical axis. u is the (vertical) projection of point P on the image plane (the scan line in the image on which the spot is detected). P_1 and P_2 are two points used in the calibration of the system; x_1, x_2, u_1, and u_2 are known.

E is the point where the path of the laser intersects the optical axis. We angle the laser such that point E is at the center of the range of interests. However, this technique also works with the laser path parallel to the optical axis. There is no particular need for accurate determination or setting of the axes, beyond a concern for precision to be discussed later. There is also no need to know the baseline distance between camera and laser, nor the focal length (f) of the camera.

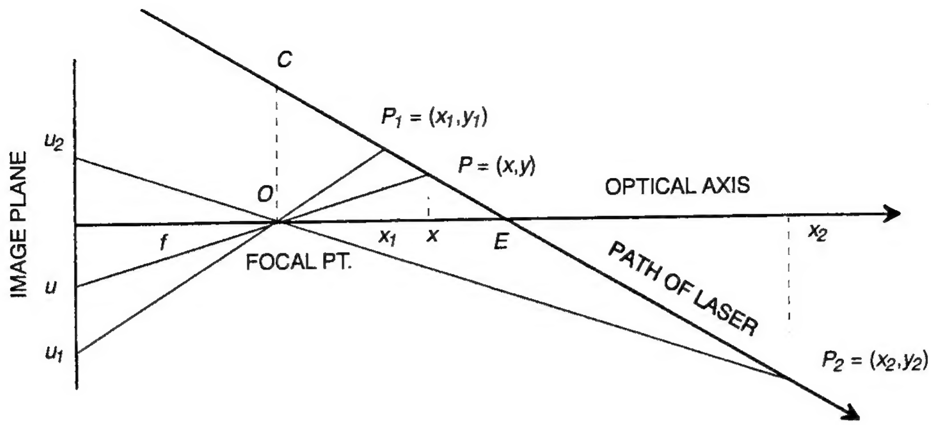

Figure 2. Setup of laser and camera.

Determination of x is achieved as follows:

From the geometry of similar triangles, we have

$$\frac{y_1}{x_1} = \frac{u_1}{f} \quad \text{and} \quad \frac{y_2}{x_2} = \frac{u_2}{f} \tag{2}$$

We place the origin of the coordinate system at the focal point, without loss of generality. The slope (m) of the laser path and the y-intercept (c, the height of point C) are:

$$m = \frac{y_2 - y_1}{x_2 - x_1} \quad \text{and} \quad c = y_2 - mx_2 \tag{3}$$

Substituting equation 2 into equation 3 to eliminate y_1 and y_2, we have:

$$m = \frac{u_2x_2 - u_1x_1}{f(x_2 - x_1)} \quad \text{and} \quad c = \frac{u_2x_2}{f} - mx_2 \tag{4}$$

We note that it is difficult to find the exact "focal point" of a given camera. However, point C in figure 2, which is directly above this focal point, can be found given measurements of y_1 and y_2 (equation 3) or knowledge of the focal length, f, (equation 4). This point can be used as the location of a "virtual" laser source, and the length OC becomes the "virtual" baseline distance. We can then proceed with the law of sines approach for range determination using these parameters.

However, f is hard to determine accurately for some lenses (e.g., zoom lenses), and y_1 and y_2 are also difficult to measure. They are the offsets perpendicular to the optical axis, not the height from the ground. Also, the optical axis does not necessarily pass through the center of the image, but varies from camera to camera.

We used a simpler method that does not require the knowledge of y_1, y_2, or f. We note that the line uP passing through O is represented by:

$$y = \frac{u}{f}x \tag{5}$$

and the laser path is of the form:

$$y = mx + c \tag{6}$$

Solving for x from equations 5 and 6, and simplifying using equation 4, we get:

$$x = \frac{N}{ud - k} \tag{7}$$

where N, d, and k are obtained after a simple calibration process, and

$$d = x_2 - x_1$$

$$k = u_2x_2 - u_1x_1 \tag{8}$$

$$N = (u_1 - u_2)x_1x_2$$

During calibration, we put targets at distances x_1 and x_2 from the camera, record the height u_1 and u_2 at which the laser spot striking the targets appear on the image, and compute d, k, and N using equation 8. Then, during range-finding operations, we simply note the height u of the laser spot in the image and use equation 7 to compute range. We can accomplish this without knowing the baseline separation or angles between the camera and laser source. Furthermore, equations 7 and 8 are insensitive to errors in the optical axis (i.e., $u' = a + u$, $u_1' = a + u_1$, $u_2' = a + u_2$ will give the same results).

IMPLEMENTATION

We used this laser triangulation technique in a project studying adaptive sensor-motor transformations (Blackburn and Nguyen, 1994). We needed depth information, but only a single video camera was available. The camera provided both visual information about the scene and the range to target via detection of the laser spot in the image. We attached a 5-mW solid-state diode laser on top of the charge-coupled device (CCD) camera, and used a red filter on the lens to increase sensitivity to the laser spot. The laser and camera combination, mounted on a pan-and-tilt unit on a mobile robot (ModBot), is shown in figure 3.

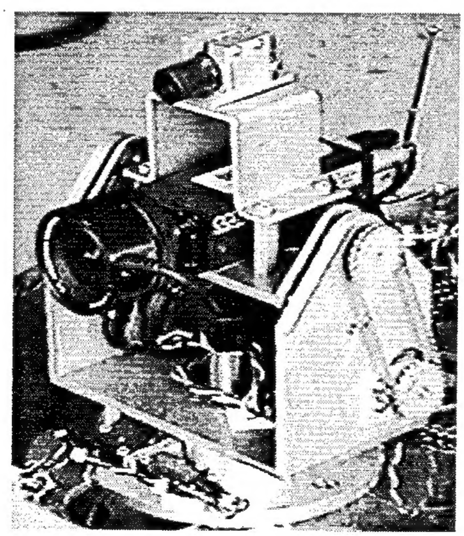

Figure 3. Laser and camera combination.

To assess target range, the target is acquired and the optical axis automatically placed at its center using the pan-and-tilt unit. The laser illuminates a spot on the target, and the vertical position of the spot in the image is used for range calculations. To accommodate small targets, the distance y (separation between laser spot and optical axis) must be kept small. This in turn means that the baseline separation between the laser source and the camera cannot be large, and the angle of the laser path must be small (fairly parallel to the optical axis). We chose to place the laser approximately 7 cm above the camera with a slight downward tilt ($E \sim 1.2$ m). The distances we were interested in were between 0.5 m and 2 m. Figure 4 shows the robot directing a remote manipulator arm to reach a cup being suspended as a target (see [Blackburn and Nguyen, 1994]).

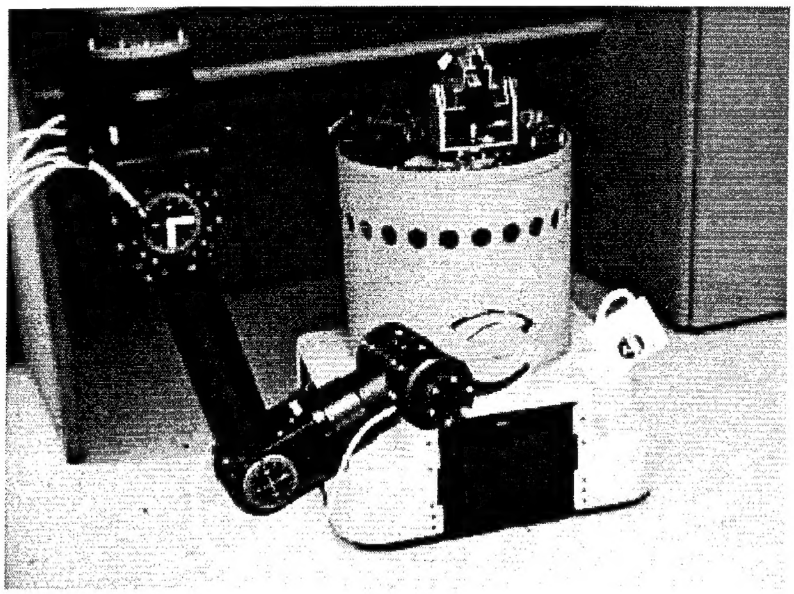

Figure 4. Robot directing remote manipulator arm.

PERFORMANCE

Our laser triangulation method is subject to a limiting factor common to all triangulation systems: reduced precision with increasing range. With the setup described above, our precision decreases from 3 mm at 30 cm to 8 cm at 1.5 m (see figure 5).

Increasing the separation distance and the laser angle will improve precision. However, in our case these are constrained by the need to keep y small. By keeping y small, we ensure that both the optical axis and the laser spot fall on the same target object (analogous to minimizing the "missing parts" problem [Everett, 1995]). Due to our somewhat unique application (i.e., motion-driven saccade mechanism), the range to target we desire is actually the distance x, and not the length *OP* (refer to figure 2), as is usually the case in most triangulation applications. But as a byproduct of keeping y small, $x \approx \overline{OP}$.

An alternate approach that would yield slightly higher precision is to use a lookup table that stores the predetermined range for every pixel height (see the Quantic Ranging System [Everett, 1995]). This would account for imperfections in the camera lens. But this approach is not appropriate for a research robot such as ModBot. Modbot's laser rangefinder is used in many applications. Each

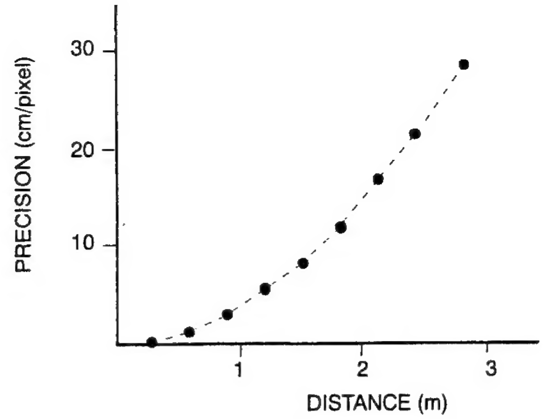

Figure 5. Precision versus range.

application requires the laser to be re-aimed to get the crossover point, *E*, at the middle of the range of interests (e.g., 1 m for manipulation tasks and 3 m for navigational tasks), and every change would require repeating a much more time-consuming calibration.

Another problem often associated with laser rangefinders is the specular reflections and absorption on different surfaces, decreasing detectability. We have noticed this on several instances in our application. We found that a red filter helped in the detection of the laser spot in most instances. Using a pulsed laser coupled with frame subtraction would also increase sensitivity. However, the tradeoff is that twice as many image frames would have to be digitized and transferred from the frame grabber to the processor board, and the current speed bottleneck in most real-time vision systems (including ours) is this frame-grabbing and transferring activity.

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13. ABSTRACT *(Maximum 200 words)*

We present the design and implementation of a simple range finder for robotic applications via laser triangulation. The technique does not require knowledge of baseline separation and angles from camera and laser to the target. The system has been successfully implemented on a mobile robot, providing range information for controlling a remote manipulator.

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